

DIRECT OBSERVATION OF THE FOURTH STAR IN THE ZETA CANCRI SYSTEM

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ABSTRACT

Direct imaging of the ζ Cnc system has resolved the fourth star in the system, which is in orbit around ζ Cnc C. The presence of the fourth star has been inferred for many years from irregularities in the motion of star C, and recently from C's spectroscopic orbit. However, its mass is close to that of C, making its non-detection puzzling. Observing at wavelengths of 1.2, 1.7, and $2.2\ \mu$ with the adaptive-optics system of the CFHT, we have obtained images which very clearly reveal star D and show it to have the color of an M2 star. Its brightness is consonant with its being *two* M stars, which are not resolved in our observations but are likely to be in a short-period orbit, thereby accounting for the large mass and the difficulty of detection at optical wavelengths, where the magnitude difference is much larger. The positions and colors of all four stars in the system are reported and are consistent with the most recent astrometric observations.

Subject headings: stars: binaries: visual, stars: individual (ζ Cancri), stars: fundamental parameters

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1. Introduction

ζ Cancri is a visual triple stellar system which has been studied as such for over 200 years. The system consists of three bright stars, all dwarfs of close to solar type with visible magnitudes near 6. The orbital planes of the system are not far from the plane of the sky. There is a close pair AB separated by about 1 arcsec with an orbital period 58.9 years, and a third star C about 6 arcsec away with an orbital period estimated at 1100 years. Star C itself has proper-motion irregularities that were first remarked upon by Sir John Herschel (1831) and were interpreted by Otto Struve (1874) in terms of orbital motion in a period on the order of 20 years around an unseen companion. Subsequent observations and discussions have corroborated Struve’s interpretation, and have recently been reinforced by a spectroscopic orbit of C by Griffin (2000), who has also described in some detail the interesting observational history of the system. The situation concerning the three visual orbits in which the ζ Cnc stars are involved (those of AB, CD, and AB–CD) have been summarized most recently by Heintz (1996). All three have appreciable eccentricity, with that of CD being lowest at 0.12.

The principal question that has remained outstanding concerning the ζ Cnc system is the nature of the companion to star C, since its orbit indicates a companion of comparable mass and a separation of about 0.4 arcsec. Griffin (2000) recounts some of the earlier claims regarding the nature of star D, and it is clear that it must be considerably fainter than C at visible wavelengths. Suggestions have consequently been made that it is a white dwarf, or else a close pair of M stars which would be quite faint in the visible. Griffin concluded that the question remained open, but that a short exposure by a large telescope with adaptive optics might provide the definitive evidence. Accordingly, the system was observed during a run with the Canada France Hawaii telescope by one of us (JBH) in January 2000, and followed up by further data from the same system a month later by another of us (FM). As we describe below, we discovered star D immediately and easily.

2. Observations and data

The observations of ζ Cnc were carried out during runs of the adaptive optics (AO) camera of the Canada France Hawaii telescope (CFHT), with the near-infrared camera KIR (see Rigaut et al 1998). They were obtained during gaps in other programs, using filters that happened to be in the camera. Thus, as described below, the observing program was not particularly well planned, but it occupied a total exposure time of under one minute! The field of view of $35'$ easily includes all of the stars in the system. The brightness of the stars made the AO correction extremely good, with FWHM close to the diffraction limit at

all wavelengths. The filters used were generally narrow-band, to avoid detector saturation and the need for very short exposures. Table 1 lists the details of the observations.

The first observations by one of us (JBH) in January 2000 used the AB pair as guide star. That proved not to be a happy choice: the two bright stars are separated by less than $1''$ and the guiding system ‘hunted’ back and forth between the two, producing double images of all the stars present, all with attendant diffraction rings! The ‘PSF’ pattern also changed depending on where in the field of view the guide star(s) were, during the dither pattern used. In spite of the complex images produced, it was clear that a companion star to C (star D) was present, and it was possible to measure its position and brightness by subtracting the complex PSF. The process was fortuitously made simpler by the fact that star D is quite well separated from C along the same direction as the separation of AB (and hence the double PSF).

Since it was clear that better results would be obtained by guiding on star C, which is effectively single at the visible wavelengths used for guiding, and in view of the possibility of measuring the relative motions of the stars over an interval of several weeks, further observations were obtained in February by one of us (FM). The AO system produced very well-corrected images from the bright guide star, with FWHM of $0''.08$, $0''.10$, and $0''.12$ at J , H , and K ; they are shown in Figure 1.

Since the stars are so bright and the exposures so short, there was no need for flat fields or sky subtraction in order to measure the star fluxes and positions. Small changes seen in the diffraction patterns are due to the shortness of the exposure times. The residual seeing halo due to any incompleteness of the AO correction is resolved into individual speckles, as is typical for short exposures on AO systems. However, we established that measurements from images dithered to different places on the detector produced values that differed by amounts too small to matter in this investigation.

3. Measurements and discussion

For each of the observing runs, the positions and fluxes of the stars were determined, using all the images taken. Fluxes were measured by the IRAF task ‘imexam’, and also by summing the signal from sections of image and subtraction of the off-star signal levels. Star positions were determined by imexam, and also by visual inspection of contour plots over the central pixels of each star image.

The camera was removed and re-installed between the two observing runs. Thus, it was necessary to check the orientation of the images for small rotations. Since systems AB

and CD moved in their orbits over the interval, we used the position angle of BC as the fiducial, since its predicted change in the interval is only $0^\circ.03$ (Heintz 1996). That check showed that a marginal rotation between runs of $0^\circ.05 \pm 0^\circ.08$ had occurred. This correction has been applied to the position-angle differences we report.

Our main interest is in relative fluxes between the system stars, so no absolute calibration was applied, except to check that the overall colors between visible and IR are as expected for the bright stars, which are all of almost the same spectral type. Table 2 shows the measurements made of fluxes and Table 3 shows the position and angle measurements.

Table 2 compares the color differences expected for main-sequence stars of various likely types, from Bessell & Brett (1988). They have been corrected from the standard *JHK* values to account for the different bandpass centres of the Fe II and Br γ filters. The spectral type of star C is quoted as G5 in the Bright Star Catalogue (Hoffleit 1982) but Griffin (2000) has argued that it is based upon a misconception and that G0 is more likely. As A and B are bright and overlapping, while C and D have different fluxes, the color differences C–D are more reliable than A–D or B–D.

As a figure of merit, we sum the differences between model and observed colors in Table 2. For B–D, that indicates that M2 is better than M0 for D, and for C–D G0+M2 fits better than G0+M0 or G5+M2. Thus, we conclude from the color differences that C and D have spectral types G0 and M2, respectively, with an uncertainty only on the order of one spectral subtype.

The mass ratio C/D is close to unity — Heintz (1996) gives masses of 0.99 and 0.93 for C and D — which does not accord with the mass ratio of single main-sequence stars of types G and M. However, if D is itself a binary system of two stars close to spectral type M2, the mass would be 0.78, and for an M0 pair it would be 0.94 (see Allen 1973). From the mass function of 0.05 found by both Griffin and Heintz, such a combined mass corresponds to an orbital inclination of about 35° .

The angle changes noted in Table 3 are fully consistent with the published orbits of Heintz (1996). Note that the orientation of our detector is based on adopting the predicted angle of BC from Heintz’s orbits. The ‘predictions’ in the table are derived from Heintz’s tables and periods, assuming a mass ratio near unity for CD. The observed separation and direction of D from C, and their changes, indicate that to be the case. Monitoring of the CD visual orbit with further AO images will enable much better estimates to be made of the mass ratio.

Given that the stars are all at the same distance, absolute magnitudes can be used to predict the magnitude difference between C and D in the *V* band as 4.5 for two M2

stars and 3.5 for two M0 stars, compared with G0 (Allen 1973). Applying the standard $(V - K)$ colors to the difference we measure between stars C and D we derive V magnitude differences of 4.1 and 3.5 for pairs of M2 and M0 stars, respectively. Thus, the colors and relative fluxes are fully consistent with stars D being an unresolved binary of two M stars. A challenge for future observations will be to resolve D at visual wavelengths and measure its V magnitude, and even to demonstrate (directly and/or spectroscopically) that it is double.

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Caption to Figure 1

Images of ζ Cnc guided on star C. N is $2^\circ.8$ left of vertical, and E to the left. Filters are J (top left, 1.2μ), Fe II cont (top right, 1.7μ), $\text{Br}\gamma$ (lower left, 2.2μ). Lower right is detail of CD pair with Fe II cont filter. CD separation is $0''.32$.

Table 1. ζ Cnc journal of observations

JD 245..	Filter	$\lambda, \Delta\lambda(\mu)$	Exp (sec)	Comment
51568.4	Br γ	2.16, 0.02	5.0	Guide on AB, 4 dither
51568.4	J cont	1.21, 0.015	5.0,2.0	Guide on AB, 5 dither
51596.2	J	1.25, 0.16	0.5	10 frames, guide on C
51596.2	Br γ	2.16, 0.02	1.0	6 frames, guide on C
51596.2	FeII cont	1.69, 0.02	0.7	5 frames, guide on C

Table 2. ζ Cnc color differences of stars

Color differences ± 0.05			
Stars	J–FeII	J–Br γ	FeII–Br γ
A–B	0.00	0.00	0.00
B–D	0.34	0.47	0.21
A–C	0.00	0.03	0.03
C–D	0.32	0.51	0.19
F9 V – M2 V	0.31	0.55	0.19
G0 V – M2 V	0.31	0.53	0.18
G5 V – M2 V	0.26	0.47	0.18
G0 V – M0 V	0.23	0.47	0.15

Table 3. ζ Cnc astrometry

Position angles are as in Heintz (1996) — from N towards E

Date/change	CD(")	CD(°)	AB(")	AB(°)
51568.4	0.336 ± 0.006	86.2 ± 1.6	0.837 ± 0.003	83.69 ± 0.35
51596.2	0.317 ± 0.003	84.5 ± 0.9	0.841 ± 0.004	82.97 ± 0.15
Heintz 51596.2			0.835	83.10
Change	-0.019 ± 0.007	1.7 ± 1.8	0.004 ± 0.005	0.72 ± 0.38
Orbit prediction	—	1.6	0.003	0.42